EXPERIMENTAL AND NUMERICAL INVESTIGATIONS ON SUSTAINABLE HIGH STRENGTH CONCRETE WITH WEATHERED CRYSTALLINE ROCK SAND AND PET FIBRE

A SYNOPSIS

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1. INTRODUCTION

1.1 High strength concrete

High strength concrete is defined as the concrete with a characteristic cube compressive strength of 60 MPa or greater as per IS 456: 2000. Conventional concrete is suitable for many common applications, high strength concrete (HSC) is engineered for specific situations where increased strength is a critical requirement and hence in recent years, demand has continued to grow for HSC for use in infrastructure development. This construction material is used in high-rise buildings to avoid the use of unacceptably oversized columns on lower floors, to allow large column spacing and more usable floor space, or to increase the overall height of the building without detracting from the aesthetics and function of the lower floors. Furthermore, because of the low permeability characteristics, high strength concrete performs much better under harsh climate conditions and in marine environments, therefore reducing maintenance and repair cost. HSC requires special care during production and testing, and may need special structural design requirements.

1.2 Weathered crystalline Rock sand

Weathered crystalline rock (WCR) is the outer layer of earth crust and also it is soft in nature. These characteristics make it easy to quarry and to produce fine aggregate in a cost effective manner. Even now people are using this by adding it to river sand but as there is not many studies have been carried out on the properties of this material, engineers don't recommend it and hence adding it to river sand is considered as adulteration. In fact in many areas before quarrying rubble, this soft outer layer of rock has to be removed and if this can be used as a substitute for the fine aggregate, it will be a solution for the disposal of a waste material. The properties of fine aggregate produced from weathered crystalline rock like strength, specific gravity, etc., are comparable with that of the manufactured fine aggregate and that of natural river sand.

1.3 Polyethylene Terephthalate bottle fibre

Polyethylene Terephthalate (PET) bottles, commonly used for packaging beverages and other liquids, exacerbate environmental problems associated with plastic bottles due to their specific characteristics and widespread use. These bottles contribute significantly to resource depletion and greenhouse gas emissions, as PET production relies heavily on fossil fuels and energy-intensive processes. Moreover, PET bottles

persist in the environment for extended periods, breaking down into micro plastics that contaminate ecosystems and harm wildlife. Their lightweight nature also facilitates their transport by wind and water, leading to widespread pollution of oceans, rivers, and landscapes. Additionally, PET bottles pose challenges for waste management systems due to their limited recyclability and low recycling rates. Hence reducing the PET bottle waste by using it in another applications like improving the tensile strength and impact strength are some of the ways of mitigating the environmental issues related with PET bottles.

1.4 Mesoscopic numerical modelling of concrete

Mesoscopic modelling in the context of concrete involves simulating the behaviour of concrete at a scale between the microscopic (individual particles) and macroscopic (bulk material) levels. This approach considers the heterogeneous nature of concrete, accounting for factors such as aggregate distribution, interfacial transition zones, and pore structure. Mesoscopic models typically utilize techniques like discrete element method (DEM), lattice-based models, or combined approaches to represent concrete constituents as discrete entities interacting with each other and the surrounding matrix. By capturing the complex interactions between aggregates, cement paste, and other components, mesoscopic modelling provides insights into phenomena like cracking, deformation, and failure mechanisms with greater detail than macroscopic models. In comparison to macroscopic models such as finite element method (FEM) or continuum models, mesoscopic modelling offers advantages in predicting localized behaviour and capturing mesoscale features, making it particularly useful for studying phenomena like fracture, creep, and durability properties of concrete structures. However, mesoscopic modelling typically requires more computational resources and detailed input parameters, posing challenges in terms of simulation time and model calibration. Overall, while macroscopic models provide a broader perspective on concrete behaviour, mesoscopic modelling offers a more detailed understanding of localized phenomena, enabling more accurate predictions and insights into the mechanics of concrete structures.

2. LITERATURE REVIEW

2.1 High strength concrete

A high-strength concrete is always a high- performance concrete, but a high-performance concrete is not always a high-strength concrete. Durable concrete specifying a high-strength concrete does not ensure that a durable concrete will be achieved. It is very difficult to get a product which simultaneously fulfils all of the properties. So the different pozzolanic materials like Ground Granulated Blast furnace Slag (GGBS), Silica Fume, Rice Husk Ash, Fly Ash, High Reactive Metakaolin, are some of the pozzolanic materials which can be used in concrete as partial replacement of cement, which are very essential ingredients to produce high performance concrete, Ahmed *et al*. [1]. It is very important to maintain the water cement ratio within the minimal range, for that we have to use the water reducing admixture i.e. superplasticizer, which plays an important role for the production of high performance concrete. So this project will test on different materials like Ground Granulated Blast Furnace Slag, and Silica Fume to obtain the desired needs. This research aims to examine the impact of FA and HSF on the durability and strength of RC concrete. The study uses two mix families (RC and NC) with FA used at different levels and HSF at different fractions. The durability and strength parameters of each concrete mixture are evaluated, and relationships between parameters are developed to understand their dependency. The ultimate goal is to create a sustainable, durable, and strong RC, Baber *et al.* [2].

2.2 Weathered crystalline rock sand

Self-compacting concrete (SCC) is an innovative concrete that does not require vibration for placing and compaction. Aggregate occupy 70-75% of the total volume of concrete. From earlier days onwards river sand is used as fine aggregate. Nowadays, M-sand, pit sand etc. are also used and since pit sand is available only at certain regions and due to the scarcity of river sand and M-sand, it has become necessary to find an alternative material, as fine aggregate. The alternative material selected here is sand from Weathered Crystalline Rock. And this type of rock is abundantly available at low cost in tropical areas. This paper discusses the fresh properties and durability of self-compacting concrete using weathered crystalline rock sand as fine aggregate, Jyothis & Ranjan [3].

This paper deals with the Taguchi regression analysis on strength of Concrete with weathered crystalline rock sand. Due to industrialisation, large constructions are going on all over the world which in turn requires huge quantity of cement and sand. In this study weathered crystalline rock sand which is obtained from the soft outer portion of rock in quarries is used as replacement for river sand and Ground Granulated Blast-furnace Slag (GGBS) obtained from iron industry is used as replacement for cement to reduce the environmental impact as well as to help waste handling and reuse, Shaji *et al.* [4].

2.3 Polyethylene Terephthalate Fibre (PET fibre)

Plastic waste has been increasing significantly due to manufacturing processes, service industries, and municipal solid waste. This has raised environmental concerns and led to the need for recycling plastic waste. One solution is using plastic waste as recycled material in concrete construction to create green concrete. Studies have shown that using polyethylene terephthalate (PET) in concrete as a volume ratio or aggregate replacement can reduce environmental pollution, carbon dioxide emissions, and plastic waste disposal issues. This research highlights the potential of PET in concrete construction, Asker *et al.* [5].

Researchers have been exploring the development of prepacked aggregate fibre reinforced concrete (PAFC), a new type of concrete. PAFC is formed by stacking coarse aggregate in a mould and filling it with liquid grout. A study aimed to improve the consistency of results in impact tests on PAFC by making five simple changes to the standard ACI 544 drop weight impact test setup. The changes included using a steel bar for a line impact, introducing notches on the specimens' surfaces for different loads, and using sand or coarse aggregate instead of a solid base plate. The study involved 108 cylindrical specimens and tested in 12 groups, with steel and polypropylene fibres added at a 2.4% dosage. The results showed that these alterations significantly reduced test results, Gunasekaran *et al.* [6].

2.4 Mesoscopic numerical modelling of concrete

Meso-scopic modelling of concrete is a promising solution for analyzing its behavior under loading, as it considers the heterogeneity of the material. Researchers have used

three-dimensional (3D) numerical Mesoscopic models to study progressive concrete fracture at aggregate level in a notched concrete beam under bending. Concrete is a highly heterogeneous material made with entirely different general properties and hence it is believed now that, this non-homogenous nature of concrete makes it challenging to predict the response to loading of numerical models. For simple numerical analysis of concrete, macro scale is commonly used but, according to Wittman et al, there can be two or three more scales of modeling possible, *viz*, Mesoscopic, Microscopic and Nano scales, Zaitsev & Wittman [7].

This paper presents a 3D mesoscale modelling approach to study the dynamic tensile properties of coral aggregate concrete (CAC). The model, consisting of tri-phase components, was used to simulate CAC under direct tension at different strain rates. The failure pattern and micro-cracking process were simulated, and stress-strain curves were obtained. The effect of strain rate on tensile properties was quantitatively analysed, and strain-rate effect laws were determined. The tensile constitutive relations of CAC at different strain rates were obtained, which is crucial for further investigation of CAC's dynamic tensile properties. The simulation results align with existing test results, proving the 3D mesoscale modelling approach a powerful tool for simulating direct-tensile behaviour and understanding damage mechanisms, Zhangyu, *et al.* [8].

2.5 Outcome of literature survey

From the extensive literature survey conducted on the relevant topic with regards to the title of research, the following points are noted:

Weathered crystalline rock sand which is a waste material or used as adulterant can be considered as a partial replacement for river sand and M-sand as fine aggregate in concrete up to some reasonable percentage. But detailed studies of requirements of WCR sand with regards to durability properties are limited or are very few especially in the case of high strength concrete. Hence the present study will shed light on the usability of WCR sand in high strength concrete.

Impact strength of high strength concrete has been a hot topic in civil engineering research area in recent times. To achieve better ductility which in turn will improve the impact strength, various types of fibres, like steel, natural fibre, fibres from waste

materials etc., are tested and the results are promising. A benefit of using waste materials in construction is the achievement of green concept and sustainability aspect of the project and waste PET bottles are one of the major concerns when we consider environmental issues around the globe. Hence the present study about impact resistance of high strength concrete using PET fibre is a hopeful area for multi-benefitted research.

With the rapid developments and evolutions in computing and computing infrastructure, numerical modelling and non-destructive testing of concrete have been two buzz phrases in the modern civil engineering research domain. An encouraging method of numerical modelling of concrete is the meso-scopic modelling of concrete. From the literatures it can be seen that lot of researches have been conducted in the area though it is a computationally heavy process and almost all of them have considered concrete as a three phase model consisting of coarse aggregate, cement mortar and interfacial zone. Modelling of mesoscopic concrete is hence a cumbersome time consuming process and if it can be simplified by any means it will be highly useful for researchers in this field. So in the present study an attempt is made to avoid modelling of the interfacial zone separately instead only the coarse aggregate and cement mortar are modelled.

In mesoscopic modelling of concrete the most difficult and time consuming part is the generation of random aggregate models. It needs a lot of parameters like size of the specimen, sieve analysis data, mix ratio, shape of the specimen, number of iterations, shape of the aggregates, etc. Many researchers have used various methods but as a result of an extensive literature and application search, it can be concluded that there is no easy and simple application available for the modelling of random aggregate. Hence in this study a simple but efficient application for the above is developed.

The need for the study and existing gaps identified from the literature review are as follows:

Need for study:

- As the natural resources are depleting very fast, alternative material is needed
- To use the WCR sand in concrete, especially in HSC, a correct assessment of the properties, viz, mechanical, durability and impact properties are necessary.
- To help the assessment of properties and response of structures, numerical modelling and software for this are needed.

From the literature study the following gaps are identified:

- Studies and literatures about WCR sand are very limited, especially for HSC
- Research works about PET fiber reinforced high strength concrete are very little
- There are very few literatures available about the 2-phase mesoscopic modelling of concrete

3 OBJECTIVES

1. To assess the strength and durability properties of high strength concrete with fine aggregate replaced by weathered crystalline rock sand with a replacement percentages of 0, 5, 10, 15 and 20.
2. To study the impact resistance of PET fibre reinforced high strength concrete using repeated drop weight test.
3. To study and develop a simplified mesoscopic numerical model of concrete and validate the models generated with regards to basic and advanced strength parameters of concrete.
4. To develop a simple and easy software application for the mesoscopic modelling of concrete.

4 RESEARCH PROBLEM

The primary research problem is to evaluate the viability and performance of sustainable high-strength concrete utilizing weathered crystalline rock sand and PET fibre reinforcement. The investigation aims to understand the influence of these materials on the basic and advanced strength parameters of concrete, including compressive strength, split tensile strength, and impact strength. An attempt is made to develop various tools both hardware and software types for facilitating the research. A software for the numerical testing of the concrete using mesoscopic modelling for various strength parameters will be developed - MesoGen, which is made freely available for other researchers also. Two hardware tools – one for the impact testing and another for extracting fibres from waste PET bottles – will also be designed and fabricated.

5 HIGH STRENGTH CONCRETE WITH WCR SAND AS PARTIAL REPLACEMENT FOR FINE AGGREGATE

5.1 Mechanical Properties - Compressive strength, split tensile strength and flexural strength test

The compressive strength test results show that replacing M-sand with WCR reduces compressive strength. Up to 15% of replacement, the concrete mix attains the characteristic compressive strength required. Water absorption tests on WCR sand showed that it absorbs more water by around 18% compared to M-sand. The more water absorbed by constituent materials other than binding materials, the more the effect on the strength of concrete.

The splitting tensile strength decreased as the percentage of M-sand replacement with WCR sand increased. This suggests that WCR sand may not be as effective as the original FA in providing tensile strength to the concrete at higher percentages of replacement. However, up to 5% replacement of FA can be considered recommendable.

Flexural strength was also tested using three beams for each variations of WCR replacement with dimensions of 100mm X 100mm X 500mm, which showed that increasing the percentage of WCR for partial replacement of FA reduced flexural strength.

5.2 Durability properties - RCPT, water penetration, sulphate resistance and abrasion resistance

Durability properties were assessed using the Rapid Chloride Permeability Test (RCPT), which showed that sand replacement of 5% with WCR gave the best results, which was "Very Low." The denser and more uniform a material, the lesser the chloride ingression.

The control mix with M-sand as the FA showed the highest depth of water penetration, while concrete with 5%, 10%, and 15% WCR replacement percentages showed lower depths. The reason for these results could be due to increased packing density, leading to a denser microstructure with fewer voids. The fines content of WCR sand is more

than that of natural sand, which can fill voids in the concrete matrix, resulting in lower permeability.

The study also found that concrete with 5% replacement exhibited the best sulphate resistance, with lowest weight loss and compressive strength loss. The strength loss of the samples with 5% and 10% replacement was very similar, suggesting that up to 10% replacement could be feasible without significantly compromising the sulphate resistance of the concrete. The control mix (0% replacement) exhibited higher weight loss compared to all other mixes, indicating its lower sulphate resistance.

The abrasion resistance values obtained from the test align with previous studies that have investigated the impact of replacing FA in concrete on its abrasion resistance. WCR sand, being abundantly available in tropical areas, so its inclusion as a replacement for FA could potentially enhance the abrasion resistance of the concrete.

5.3 Scanning Electron Microscopic analysis

Scanning Electron Microscopic (SEM) analysis of the control specimen and WCR replaced concretes for 5% and 10% revealed that the sample with WCR replacement of 5% is denser and the control mix has more inter molecular pores, while concrete with 10% replacements seems to be less dense and non-uniform.

6 HIGH STRENGTH CONCRETE WITH PET FIBRE REINFORCEMENT AND WCR SAND AS PARTIAL REPLACEMENT OF FINE AGGREGATE

Concrete is being a brittle material, its durability can be enhanced by including fibres into the mixtures. This study focuses on polyethylene terephthalate (PET) fibre derived from PET bottles. PET fibre possesses several benefits including high tensile strength, durability, chemical resistance, crack control, and fracture control. Utilizing recyclable PET fibres can help mitigate environmental issues linked to PET bottles, including resource depletion, greenhouse gas emissions, and pollution. Through the process of transitioning PET bottles into fibres for reinforcement, substantial quantities of plastic trash are redirected away from landfills and oceans, thereby diminishing plastic pollution. This novel method not only enhances the durability, resistance to cracks, and

flexibility of concrete but also decreases the need on new materials such as steel, thereby preserving natural resources and minimizing environmental consequences.

6.1 Mechanical Properties

To assess the mechanical strength of PET fibre reinforced WCR concrete, testing the compressive strength, split tensile strength, flexural strength and the impact strength were the primary aims of the study. As the results from the mechanical strength tests conducted on plain concrete without PET fibres show that 5% replacement of fine aggregate is advisable, the specimens with 5% WCR replacement only are used in fibre reinforced concrete.

6.2 Compressive strength test

The compressive strength test was carried out in accordance with the specifications provided in IS 456:2000. 35 numbers of 150mm x 150mm x 150 mm cubes were casted cured ponding and tested after 28 days. The findings indicated that the inclusion of PET fibres caused the concrete to show reduced compressive strength for all the variations of fibre percentage.

6.3 Split tensile strength test

The split tensile test of concrete involved casting of 21 cylinders, three for each variation of the percentage of PET fibre content (with 5% WCR sand). The specimens were stored in a curing tank for 28 days to ensure proper hydration. After curing, the cylinders were tested in compliance with Indian Standard IS: 5816 – 1999. The load was incrementally applied at an approximate rate of 140 kg/cm² per minute until a significant decrease in the specimen's resistance to the increasing load was observed or until the specimen failed. From the results, it is seen that the split tensile strength of PET fibre concrete has increased up to 1% of pet fibre volume and then decreased.

6.4 Flexural strength test

To assess the flexural strength of PET fibre reinforced high strength concrete (with 5% WCR sand), 21 specimens having dimensions 100mm x 100m x 500mm were cast to represent each variation of PET fibre percentage. The specimens underwent a 28-day curing procedure in a moisture-controlled environment to ensure optimal hydration of cement particles. The specimen was subjected to an increasing load until the specimen failed or there was a noticeable decline in its resistance. The tests show that the flexural

strength also was varying in a similar manner as that of split tensile strength initially increasing up to 0.75% of PET fibre and then decreasing.

6.5 Advanced Mechanical Properties – Impact strength

A total of 42 discs, 150mm in diameter and 65mm in height, were subjected to impact strength test. The discs had various fibre content ranging from 0% to 1.5%. The findings indicate that including PET waste fibre into High Strength Concrete has a beneficial effect on its resistance to impact. This is evident from the enhancements observed in both the number of blows needed to cause the first hairline crack (N1) and the failure crack (N2). The addition of more fibres in the material led to significant improvements, with N1 impact increasing by 33-125% and N2 by 31-122%. More precisely, N1 showed a 53% enhancement with a fibre volume of 0.5% and an impressive 126% enhancement with a fibre volume of 1.5%. Similarly, the improvements for N2 started at 63% with 0.5% fibre and reached 123% with 1.5% fibre. The findings indicate that the impact strength of concrete is positively correlated with the proportion of PET fibres. This is because the dispersion of PET fibres throughout the concrete matrix contributes to enhanced strength. When an external force is exerted, these fibres assist in evenly dispersing stress across the concrete, so inhibiting the formation and propagation of cracks. This reinforcement technique significantly improves the structural integrity of the concrete, rendering it more resilient against impact. The test setup according to ACI 544 is shown in Figure. 1.

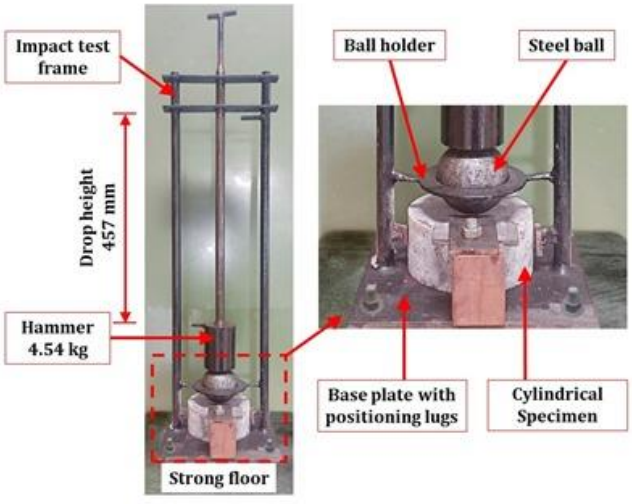

Figure.1. Repeated Drop weight Impact Testing Machine

7 NUMERICAL EVALUATION OF CONCRETE USING MESOSCOPIC MODELLING

The evaluation of heterogeneity of concrete at mesoscopic level requires generation of a random aggregate structure in which the shape, size and distribution of the coarse aggregate closely resemble real concrete in the statistical sense. The spatial distribution of the aggregate particles is the most important factor in determining how the matrix material will be laid out. For the spatial arrangement of the particles to be as uniform and isotropic as is practically achievable on a macroscopic scale, the random sampling approach of the Monte Carlo simulation is used to produce the geometrical configurations. While placing each of the particles in Mesoscopic model using this method, selecting aggregate samples following a grading curve from sieve analysis, another requirement of overlap of particles has also to be avoided.

8 DEVELOPMENT OF ANDROID APPLICATION – MESOGEN - FOR THE AUTOMATIC GENERATION OF MESOSCOPIC MODEL

Aggregate modelling in mesoscale analysis is only possible using computer programs as parameters of concrete like mix ratio, specimen dimensions, volume of aggregates, etc., are to be varied with different requirements. Difficulty in changing these parameters at runtime will be solved by MesoGen, the developed software. Android phones are very convenient and development and distribution of applications is comparatively faster than other platforms, hence for the time being, the development platform is restricted to android. Using this application, 3D models are generated and are exported into various formats for numerical testing using appropriate software. The benefits of this application is that to generate mesoscopic model of concrete, anyone can easily vary the concrete mix, aggregate sieve analysis data, dimensions of the specimen, shape of the specimen, viz, rectangular or circular section, aggregate volume ratio and number of iterations. The data used for generation of one model can be saved and reused in the same form or edited. Also as it is an android application which can be installed on android phones, the generation can be done anytime anywhere.

9 GENERATION OF MESOSCOPIC MODELS OF CONCRETE AND TESTING USING FINITE ELEMENT ANALYSIS SOFTWARE

Using the developed android application MesoGen, various mesoscopic models, viz, the cubical, cylindrical shaped concrete numerical models were generated and tested

in finite element analysis software, Ansys. Using the app, it was possible to generate aggregates with spherical shape and non-spherical shape resembling actual shape of aggregates. When the experimental crack pattern was compared with that of the numerical model, similarity of cracks were found.

10 RESULTS AND DISCUSSIONS

10.1 Properties of fresh high strength concrete with WCR sand partially replaced

Workability test was conducted on three samples for each variation of the WCR sand replacement, that is, 0, 5, 10, 15 and 20 percentages, the results show that 5% WCR replacement increased the workability by 3% and then it decreased. The reason may be due to the fact, the WCR sand contains more fines and also the water absorption is more compared to the m-sand and hence the workability gradually reduced beyond the 5% replacement.

10.2 Properties of hardened high strength concrete with WCR sand as partial replacement of fine aggregate

To assess the compressive strength of high strength concrete with fine aggregate replaced partially with WCR sand percentage as 0, 5, 10, 15 and 20, 15 cubes of 150mm x 150mm x 150mm dimensions were tested after curing for 28 days in curing tank. The results showed that the compressive strength of control mix with 0% WCR replacement had the maximum compressive strength of 77.2 MPa and the strength for 5% WCR replacement had a compressive strength of 75.2 MPa and that for 10% replacement, it was 72 MPa. From the compressive strength values it can be inferred that, addition of WCR sand as partial replacement for FA in concrete is recommendable in the range of 5-10% maximum even though the concrete with 10 % WCR replacement is having lesser strength than the target mean strength, but the variation with control mix is minimal when compared with 20% replacement. Other mechanical properties like split tensile strength, flexural strength tests, also showed similar trend of decreasing with increase in percentage replacement. Hence it is advisable to use WCR sand as partial replacement in the range of 5-10 %.

10.3 Durability properties of high strength concrete with WCR sand as partial replacement

To assess the long term durability properties of the high strength concrete with FA replaced partially with WCR sand, durability tests – Water penetration, rapid chloride penetration, sulphate resistance, abrasion test - were conducted on the samples after a curing period of 90 days. The rapid chloride penetration test results showed that, the concrete mix with 5% replacement of FA is having the best resistance when the results compared with the chart given in ASTM C1202-19 and the penetration was “very low” with a value ranging between 100 and 1000, which is recommended for prevention of corrosion of reinforcement and deterioration of the concrete itself. With regards to the water penetration test, on increasing the WCR sand percentage, the depth of penetration also increased but the mix with 5% and 10% replacement showed better resistance compared to other higher replacements. The sulphate resistance of the high strength concrete was assessed using loss of weight and loss of compressive strength methods. The result data shows that for 5% and 10 % replacement, the concrete showed maximum resistance to sulphate attack. Increasing the percentage of WCR drastically affected the resistance and the constituent material would have reacted with the chemicals and more amount of WCR will obviously will have more adverse effect. The abrasion resistance was also conducted using the method of measuring the loss in thickness of concrete cubes and the results showed that 5 % variation has the best resistance compared to the control mix. The reason seems to be obvious from the SEM results, which shows a uniform and dense microstructure for 5% replacement.

10.4 Mechanical strength of PET fibre reinforced high strength concrete with WCR sand as partial replacement

To reduce the brittle behaviour of concrete with WCR sand partially replaced, in the present study an attempt was made to use PET fibres extracted from waste PET bottles as reinforcement. The length of fibres were in the range of 20 to 40 mm and width of average 4mm with an average aspect ratio of 0.2. Percentage of PET fibre volume was varied from 0 to 1.5. To assess the effect of PET fibres on the other mechanical strength properties of high strength concrete, compressive strength test, flexural strength, split tensile strength tests, etc., were conducted. The results showed that compressive strength was gradually decreasing with the increase in PET fibre percentage compared to the control mix without the fibre. The compressive strength was gradually decreasing

from 77.2 MPa to 55 MPa, with the increase in the fibre percentage up to 1.5 whereas the split tensile strength and flexural strength was increased by 20% for 1.0 percentage of PET fibre volume compared with that of control mix and then decreased. The reason for the decrease in compressive strength is the loss in cohesiveness and also the uniformity of the mix with increase in fibre percentage in the concrete volume. But the fibres offer better resistance to tensile loads as the fibres offer resistance both as a binding agent and also pull out strength.

10.5 Impact strength of PET fibre reinforced high strength concrete with WCR sand as partial replacement using repeated drop weight impact test

The results demonstrate that the addition of PET waste fibre to High Strength Concrete positively affects its impact resistance, as evidenced by improvements in both the number of blows required for first crack impact (N1) and failure crack (N2). Increasing the volume fraction of fibres results in notable enhancements, with N1 impact improving by 33-125% and N2 by 31-122%. Specifically, with larger fibre volumes, N1 experiences a 53% improvement with 0.5% fibre and a remarkable 126% improvement with 1.5% fibre. Similarly, for N2, enhancements begin at 63% with 0.5% fibre and reach 123% with 1.5% fibre. These findings underscore the significant potential of incorporating PET waste fibre into High Strength Concrete for enhancing its impact resistance, particularly with higher fibre volumes.

10.6 Meso-scopic modelling of concrete using the application

Using the developed software, meso-scopic aggregate models were generated based upon the sieve data from sieve analysis conducted on various samples of aggregate. It was observed that a good number of aggregates were having lesser diameter than the minimum diameter for coarse aggregate, ie, 4.75 mm. The reason for this is found to be the repeated reduction in the radius of randomly generated particles after the given number of iterations, again and again. So this volume has to be removed from the aggregate list. After this process, the total count of particles generated is agreeing with that in the real aggregate sample sieve data except for the smallest segment, that is, 10-4.75 mm. For eg, for sieve data from table 3, the count of grains generated using MesoGen is 2465 while the number of particles in the actual aggregate sample was approximately 1827. But removal of the smaller size particles generated will affect the

AVR of the sample. The calculated aggregate volume ratio as per equation (1) for M25 mix using the sieve data in Table 6 in the application is 0.5167 but the generated volume after removing the particles with diameter less than 4.75mm is only 0.419. So the AVR to be used in the application must be factored with a value, for example, 1.3 for the sample mentioned above. Other parameters while generating the aggregates are the number of iterations (NoI) and radius reduction factor (RRF). The values used for the above sample are 10 and 0.9 for NoI and RRF respectively. In the app the lowest value available for number of iterations is 10 and this can be increased to 100, 500, 1000, etc. Increase in this number will produce better results in terms of aggregate volume ratio but it will increase the generation time drastically. The other parameter, RRF, can also be increased like, 0.95. 0.99, 0.999, 0.9999, etc. to produce better AVR, but just like the NoI, increase in RRF also will increase the generation time. A comparison has shown that, if NoI = 10 and RRF = 0.9, then the generation time can be as low as 5 seconds for the above sample while if NoI = 1000 and RRF = 0.9999, the time of aggregate volume generation may be around 45.00 minutes or more. From the above aggregate models generated using the sieve analysis data of real samples, it can be seen that the number of particles and the aggregate volume ratio are very near to the experimental results.

10.7 Comparison of real sample testing with numerical sample for crack pattern

Upon importing into Ansys, an industry-standard FEM software, the specimen was subjected a compressive load of 1650kN was applied to the upper surface to assess the material's load-bearing capabilities. Linear tetrahedral elements were employed for both aggregates and mortar, offering a granular view of internal stresses. Command snippets were used to assign SOLID65 elements for mortar elements, reflecting their unique material properties as given in Table 1.

Table 1 Properties of mortar and coarse aggregate in the mesoscopic model

No	Property	Mortar	Coarse Aggregate
1	Young's Modulus (MPa)	40000	70000
2	Poisson's Ratio	0.15	0.2

These values were carefully chosen to mirror real-world materials, ensuring that the model's predictions are as realistic as possible. Once the analysis was completed, results were obtained that shed light on how such a specimen would behave under significant compressive stress. The data revealed intricate details about stress concentrations, potential cracking points, and overall structural integrity. This information is invaluable for engineers and material scientists seeking to design more resilient concrete structures. Post-processing plays an integral role in interpreting FEA results; it transforms raw data into visual representations that are easier to understand. Command snippets were utilized once again to display crack development within the specimen. This visual aid not only helps in identifying weak points but also provides a clear picture of how cracks propagate through concrete under load. To ensure that these numerical predictions held up against empirical evidence, validation was necessary. A compressive strength test was conducted on a 150mm cube concrete specimen with grade M65—a standard measure for high-strength concrete. This physical test subjected the specimen to similar conditions as those simulated in Ansys, providing a direct comparison between predicted and actual behaviour as shown in Figure. 2.

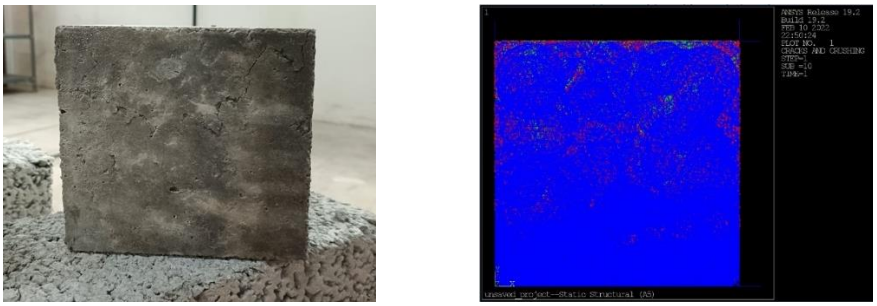

Figure 2. Comparison of crack patterns

11 ORGANISATION OF THESIS

Chapter 1: Introduction – This section provides an overview of high strength concrete, waste materials, sustainable concrete, and construction practices. It covers fine aggregates, environmental impacts, and benefits of using sustainable materials. The chapter also discusses testing methods, numerical modelling, and Weibull's distribution.

Chapter 2: Literature Review – This chapter reviews key areas in concrete technology, including strength, durability, numerical modelling, and statistical

reliability analysis. Researchers explore fine aggregate replacement, fibre-reinforced concrete and mesoscale numerical modelling.

Chapter 3: High strength WCR concrete – In this chapter, investigation methods of various strength and durability properties of high strength concrete made by replacing fine aggregate with Weathered Crystalline Rock sand partially are described. In this chapter towards the end, the results and discussions with regards to the strength and durability properties of high strength WCR concrete will be given.

Chapter 4: Properties of PET fibre reinforced WCR HSC – This chapter discusses the assessment of high strength concrete with fine aggregate partially replaced with WCR sand and PET fibre reinforcement. It details the basic and advanced strength parameters, including compressive strength, flexural strength, and split tensile strength, and the impact strength using repeated drop weight impact testing. The chapter also details the design and fabrication process of the test setup and the results obtained from the study.

Chapter 5: Mesoscopic numerical modelling of concrete – This chapter discusses the emerging field of mesoscopic numerical modelling and testing of concrete, focusing on the use of computers and IT infrastructure. It details the development of a software tool to simplify the complex process of mesoscopic modelling, and discusses the results and comparison of the mesoscopic model's performance with real test results.

Chapter 7: Conclusions – This chapter summarises the outcomes of the experimental numerical testing of the models and also the achievements of various objectives of this research work.

12 CONCLUSIONS

12.1 Mechanical and durability properties of high strength concrete with WCR sand partially replaced

The study found that using WCR sand as a replacement for FA significantly improved the mechanical and durability properties of High Strength Concrete (HSC). Although compressive strength, tensile strength, and flexural strength decreased with increasing replacement percentage, the reduction was less than 1% for 5% and similar for 10% compared to the control mix. Concrete with a replacement rate of 5 to 10% exhibited the best combination of mechanical, durability, and microstructural properties. The

study concluded that up to a maximum of 10% replacement level, WCR sand maintains compressive strength and improves durability properties. Workability improved by around 3% with 5% replacement with WCR. WCR added concrete showed reduced chloride penetrability, water penetration, enhanced sulphate resistance, and superior abrasion resistance. The study supports the use of locally available wastes for high-performance construction materials, contributing to sustainable methods and materials in the construction industry.

12.2 Impact strength of PET fibre reinforced high strength concrete with fine aggregate partially replaced with WCR sand

The study found that the inclusion of PET fibres in High Strength Concrete increased its impact strength by up to 1.5% compared to plain concrete. PET fibres distribute stress throughout the concrete matrix, preventing cracks from forming and spreading. However, the addition of PET fibres did not enhance the compressive strength of High Strength Concrete. Plain concrete showed brittle behaviour, while fibrous concrete had higher bridging action. The crack width of plain concrete decreased from 0.5 to 5mm to 0.5 mm to 2.5 mm in fibrous concrete. The presence of fibres also increased the concrete's abrasive resistance, making it less susceptible to penetration by abrasive particles. The study suggests that reusing PET fibres from recycled plastics can enhance sustainability in the construction industry.

12.3 Mesoscopic Modelling of concrete

The conventional numerical models of concrete are complex due to the homogeneity of the material. Mesoscale modelling, which involves comparing samples from the same batch, can increase accuracy by incorporating aggregate particles separately. The study found that random position and radius for each particle were selected using Monte Carloe's method. The radius of the aggregate was reduced with a radius reduction factor, making code implementation easier.

12.4 Development of MesoGen – application for mesoscopic modelling

The developed app is available as freeware. Mesoscopic model of concretes having various size, shape and aggregate volume ratio were easily generated with the app.

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14 List of publications

1. Shaji M Jamal, Neelakantan T.R., Meyyappan Palaniappan, MesoGen—Development of an Android application for the Mesoscopic modelling of concrete, *SoftwareX*, **21**, 2023.
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3. Shaji M Jamal, Palaniappan Meyyappan, Strength and durability assessment of high-strength concrete with weathered crystalline rock waste as a sustainable partial replacement for fine aggregate, *Matéria (Rio J.)*, **29** (2) 2024.